How do we establish life cycle assessment methods to assess the impact of agricultural production on soil functions?

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ABSTRACT

Soil quality attributes, and their contribution to soil function, are inherently linked to agricultural productivity, and the long-term sustainability of agriculture relies on protecting and improving our soils. The influence of soil quality on productivity and ecosystem services has been under-represented in Life Cycle Assessment (LCA) to date. Recent efforts by the UNEP-SETAC Life Cycle Initiative and the European Commission JRC have devised impact assessment frameworks that capture the ecosystem service functions of land, including soil functions. However, there is still ambiguity over the terms used to describe soil processes, elementary flows, and impact indicators. This paper explores important soil processes, identifies how elementary flows can be estimated, and explores how different aspects of soil quality can be characterised to give an integrated assessment of impact. In doing this, we define the language and terms used in the impact pathway that will help delineate inventory development from development of impact assessment methods. We discuss how the tools now available, through the growth of GIS data on land use, soils, and climate, open up the opportunity to parametrise LCI directly with the relevant elementary flows and construct LCIA methods, so that they are matched to real production systems.

Keywords: soil processes, baseline properties, biomass production, elementary flows, life cycle impact assessment.

1. Introduction

Soil quality attributes, and their contribution to soil function, are important environmental values as they are inherently linked to agricultural productivity and long-term sustainability of farming operations. In this paper, we consider soil functions that are important from the perspective of biomass production and related ecosystem services. Broader soil functions such as the provision of building materials, anchoring support for human structures and protection of archaeological treasures are not directly covered.

Many processes in the soil that affect soil quality, and subsequently soil functions, are influenced by farming inputs such as fertiliser, management activities such as tillage practices, and the type and quantity of product produced and exported from the land. When considering soil function in a life cycle assessment (LCA) context, it is important that the impact of these agricultural interventions can be reliably assessed so that the choice of alternatives, such as synthetic versus organic fertiliser, can be compared across a comprehensive range of impact categories. Supply chain participants can then use LCA to benchmark the environmental performance of current practices and identify ways in which this profile can be improved, acknowledging that there may be trade-offs between alternative practices.

Soil qualities, and the contribution they make to soil function, have not been widely included in LCA studies, and this offers the opportunity to develop methods that are purpose-built, recognising the challenges that come with land-based production systems. Once the goal and scope of an LCA have been defined, there are two distinct phases before results can be interpreted – the collection of information related to the production system ("technosphere") where the fate of substances is managed (as represented by life cycle inventory, LCI), and the assessment of impact on the natural environment ("ecosphere", as represented by life cycle impact assessment, LCIA). The challenge with land-based agricultural systems is that there is not a clear delineation between technosphere and ecosphere, with the soil being considered as part of the agricultural "factory" while also being a resource from nature. The issue then arises as to whether changes in the soil should be included in modelling the LCI or LCIA.

For some impact categories such as global warming and eutrophication, a precedent has been established for soil carbon, nitrous oxide (both direct and indirect), nitrogen and phosphorus to be included as inventory elementary flows (European Commission Joint Research Centre 2010). There has been considerable consultation on how pesticides should be modelled, with the consensus being that primary distributions to the various compartments (soil, air, water) should be included in LCI, while movement of pesticides through secondary processes (such as leaching or run-off) should be reported with inventory to inform LCIA (van Zelm *et al.* 2014; Rosenbaum *et al.* 2015).

To date, the work on soil function from an LCI perspective and from the perspective of land use impact assessment has not been well integrated. A large body of scientific research exists describing the impact that agricultural practices have on soil quality measures (SoCo Project Team 2009). Since it is a broad, integrative, and context-dependent concept, soil quality cannot easily be described by direct measurement. Instead the combination of several proxy measurements (e.g. soil pH, organic matter, bulk density) may provide indicators of how well the soil is functioning. While methods exist for assessing soil quality, the range and complexity of indicators used is not consistent, and there is little international agreement on a harmonised framework (Nortcliff 2002). The most prevalent research theme on soil quality focuses on indicator selection and evaluation (Karlen *et al.* 2003). Some authors have also contributed to the development of LCA that includes aspects of soil quality (Garrigues *et al.* 2013; Núñez *et al.* 2012; Oberholzer *et al.* 2012). However, it still remains for the LCA community to clearly articulate how these soil quality measures will be integrated into impact assessment, involving the development of new impact pathways and the connection with existing related impact pathways (e.g. climate regulation and biodiversity).

Considerable thought has gone into defining parts of the impact assessment pathways for soil function and land use (Garrigues *et al.* 2013; Koellner and Geyer 2013; Núñez *et al.* 2012; Oberholzer *et al.* 2012; Saad *et al.* 2013). Two recent initiatives, by the UNEP-SETAC Life Cycle Initiative and the European Commission Joint Research Centre, have drawn on these studies to devised impact assessment frameworks that capture the ecosystem service functions of land, including soil functions. The focus of the former has been to develop an impact pathway for biodiversity (Figure 1), while the latter has been in response to the need for a common approach to impact assessment of land use in the context of Product Environmental Footprints (PEF), with a specific focus on soil function (Figure 2).

While there is considerable overlap between these two impact pathways, there are areas of ambiguity, particularly regarding the definition of soil processes, LCI flows and LCIA mid-point indicators for soil function. To explore this area in more detail, a workshop was organised by a consortium of agencies (ADEME, France; Agroscope, Switzerland; CIRAD, France; CSIRO, Australia; EC JRC, Italy; and Life Cycle Strategies, Australia), which was held in conjunction with the Life Cycle Management Conference in Bordeaux in late August 2015. It was attended by 38 LCA scientists. The goals of the workshop were to build a shared understanding of the soil issues and research being undertaken, develop a roadmap for progressing the integration of soil function into LCA, and form an information network of relevant researchers and organisations. The format of the workshop was inspired by the Pesticide Consensus Group workshops (Rosenbaum *et al.* 2015).

An action from the soil workshop was to develop a framework for discussion by the international LCA community on integrating soil function into LCA that: 1) identifies all processes connected to soil quality; 2) establishes definitions for terms and the language used to discuss soil function; 3) indicates where these processes should be considered as elementary flows in inventory or parts of the impact pathway ; 4) establishes more broadly which impact categories elementary flows contribute to; and 5) proposes a characterisation factor that allows diverse soil quality measures to be aggregated for impact assessment. This is an ambitious task and this paper starts the framework development by defining language, proposing what soil attributes are best described by elementary flows in LCI, identifying what impact pathways soil quality measures contribute to, and suggesting a possible approach to characterisation of aggregated soil impacts. These formed topics for further discussion at a follow-up workshop in Dublin, held in conjunction with LCAFood2016 Conference in October 2016, and will subsequently contribute to discussions in the UNEP-SETAC Sub-Task on Ecosystem Services.

2. Methods

The language of soil quality in an LCA context: Agreed language and a common understanding of the terms we use in LCA are essential for productive discussions on developing soil quality as a mid-point indicator for impact assessment end-points. In this paper we propose the use of the following terms and definitions as detailed in Table 1.

Table 1. Terms and definitions used in reference to soil quality, soil function and LCA

Term	**Definition**
Soil quality	The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen *et al.* 1997).
Soil quality measures	Measures that can be made on soil to indicate an improvement or a deterioration in soil quality, that affects the ability of soils to deliver important functions.
Soil function	Important functions that soils deliver: nutrient cycling, water regulation, biodiversity and habitat, filtering and buffering, and physical stability/support (soilquality.org 2011).
Soil process	Physical, chemical or biological processes that occurs in the soil.
Soil baseline properties	Baseline measure of intrinsic/inherent soil properties to be taken into account to determine impact or as a point of comparison. This baseline condition is distinct from the "reference state" used in LCIA, although baseline properties may be used for both.
Input, activity data or inventory reference flow	Input, farming practice or output from the production system that influences soil processes.
Inventory elementary flow	An emission or resource flow to or from the technosphere to the ecosphere, caused by the effect that an input, farming practice or output has on a soil process.
Midpoint impact	Intermediate impact along the cause-effect chain that relates changes in soil quality and function to subsequent related impact categories, e.g. biomass production and climate change.
Endpoint impacts	Impacts at the end of the environmental cause-effect chain, close to areas of protection.
Areas of protection	Currently resource use, ecosystem quality and human health.

Is soil part of the farm "factory" or part of nature? The boundary between technosphere and ecosphere is used to define what elementary flows should be in the LCI and what downstream effects are represented in LCIA. Estimating elementary flows between the technosphere and ecosphere becomes more complex for agriculture where the soil on the farm forms an important part of the technosphere but is also considered to be a natural resource within which an environmental impact can occur. The balance between these can vary depending on land use, where the soil under arable use could be considered as a "highly manipulated ecosystem" (van Zelm *et al.* 2014), hence part of the technosphere, while soil in extensive grazing land may be considered as part of the ecosphere.

Flows associated with agriculture can be categorised into three classes: those that are clear emissions to nature e.g. N_2O from fertiliser use; those that accumulate or deplete resources within the field boundary e.g. hydrogen ions causing soil acidity; and those that leave with the product e.g. heavy metals from fertiliser taken up by plant products. Guidance from the ILCD Hand book (European Commission Joint Research Centre 2010) is that all of these flows should be recorded in the inventory, indicating that agricultural soil should be considered as part of the technosphere. The Pesticide Consensus Working Group (Rosenbaum *et al.* 2015) have reached the same conclusion, recommending that primary pesticide flows to air, soil and water should be included in LCI. The critical issue is to ensure that LCI and impact assessment methods are aligned so that there is no overlap in the modelling and neither double counting nor missing flows distort the impact burden.

From the soil quality perspective, we assume that flows associated with soil processes that are important to soil functions should be included in LCI, in order to better account for the influence of practices. This would call for agricultural soil be treated as part of the technosphere. However, this raises the issue of how damage to the technosphere (the soil) is accounted for in impact assessment, as damage to the technosphere in this context is important. For example, an increase in soil acidity needs to be considered differently to damage to the floor of an industrial factory during use.

3. Results and Discussion

Establishing the framework: Based on the premise that agricultural soil is part of the technosphere, we have developed a framework for linking soil processes through to the impact on soil functions. We first define all the relevant soil process (Table 2). We then considered what might be important soil baseline properties that would need to be used to set the context of a particular elementary flow. Where the LCI has been regionally defined, this information could be documented in LCI as many of the soil attributes for the region under study are accessible as GIS data. However, the intended use of soil baseline properties is for impact assessment. For example, the elementary flow of hydrogen ions which makes soil more acid has an impact only once a critical soil pH is reached. Time to critical pH is a function of the starting pH and the inherent buffering capacity of the soil. Hence, to make an impact assessment of a change in flow of hydrogen ions these two pieces of information would be required for the system under study.

Once important soil processes are identified, the next step for inventory development is to understand how these are influenced by agriculture. For each of the soil processes we have identified which inputs (e.g. fertiliser, pesticides), activity data (e.g. tillage practices, irrigation) and reference flows (e.g. yield of product) have an effect. For instance, mineralisation of organic matter (and the reverse process of immobilisation) is influenced by tillage practices (e.g. no-till versus conventional), residue management (e.g. burning versus retaining stubble), and N fertiliser rates (through the effect that fertiliser quantity has on yield and subsequent quantity of crop residue returned to the soil).

The next step is to define and quantify the elementary flows that occur due to the effect that the inputs, activities and reference flows have on soil processes. When selecting elementary flows some principles need to be considered: flows need to be additive in a linear manner (i.e. twice as much is twice as bad/good); they should be modelled as substance flows (i.e. clearly inventory flows rather than impact assessment indicators); and should be generic and applicable in all regions and countries. In Table 2 we suggest appropriate elementary flows resulting from each of the soil processes. Many of these are familiar to LCA practitioners as they are elementary flows that are used for established impact assessment methods (e. g. CO_2, N_2O and NH_3 to air, N and P to water), while others are new as they are specific to the impact of agriculture on soil (e.g. sodium to soil) or because they have not been considered in current impact assessment methods (e.g. hydrogen ions to soil water).

The final step is to identify which impact categories these elementary flows contribute to, as some elementary flows from soil processes will be picked up by multiple impact pathways. The flow of biogenic CO_2 from soil as the result of mineralisation of organic matter will contribute to both soil's function to produce biomass, and climate regulation. Likewise, the flow of hydrogen ions to soil water contributes to the acidification impact category as well as soil function, while soil loss also contributes to eutrophication (via transported P to water ways) and respiratory inorganics (from airborne soil particles). Identifying all the impact pathways is an important step in making sure elementary flows are fully accounted for and aspects of environmental damage are not overlooked.

Untangling impact pathways that include soil function: The impact pathways described by the UNEP-SETAC Life Cycle Initiative (Figure 1) and the European Commission Joint Research Centre (Figure 2), originate from the perspective that land use is the intervention documented in the inventory, and impacts are then ascribed to particular land uses. This approach results in many of the mid-point indicators being soil processes (erosion, mineralisation of SOC, physical-chemical soil conditions). For example, in Figure 1 there is a pathway from compaction to soil stability to erosion. How does this connect to a soil function? Soil stability (in terms of reduced losses through erosion) could be simply connected to the soil function of biomass production, as we indicate in Table 2 but this is not at all the perspective in the framework in Figure 1, where “biotic production” and “erosion/regulation” are on the same level as midpoint indicators. We need to address these disconnects to be able to advance our thinking about how to incorporate soil function into LCA.

Table 2. Proposed framework for considering important soil processes, baseline properties for impact assessment, the relationship between soil processes and the agricultural system, the elementary flows produced by each soil process and the impact indicators to which these elementary flows contribute.

Soil process	**Soil baseline properties**	**Input, activity data (farming practice), or output from the production system that affect soil process**	**Inventory elementary flow for soil processes**	**Midpoint impact assessment indicator**
Mineralisation and immobilisation of organic matter	Stock of soil organic carbon (SOC)	Tillage practice; Crop residue management; N fertiliser (~ yield→crop residues); Organic fertiliser; Irrigation	Biogenic CO_2 from and to air N_2O to air	Biomass production Climate regulation
Acidification	pH pH buffering capacity	Yield of product exported; Crop residues retained; Off-farm biomass inputs (manure, purchased fodder); N fertiliser (type and quantity); Lime	Hydrogen ions to soil water (accumulation within the technosphere)	Biomass production Acidification
Erosion	Slope Vegetation cover Soil texture Organic matter content	Tillage practice; Irrigation; Modification of slope and vegetation cover; P fertiliser	Tonnes of soil to air/water Kg P to water	Biomass production Eutrophication (soil-bound P to water) Respiratory inorganics (airborne soil particles) Climate regulation (oxidation of SOC in air borne soil particles)
Volatilisation of N compounds		N Fertiliser application rate Timing of fertiliser application	NH_3 to air	Acidification Climate regulation
Denitrification of N compounds		Irrigation N Fertiliser application rate Timing of fertiliser application	Emission of N_2O, NO_x to air	Climate regulation Acidification Eutrophication
Aggregation	Bulk density of native soil	Tillage practice	Change in bulk density (accumulation within the technosphere)	Biomass production
Salinisation	Natural depth of water table Sodium stock in soil water	Irrigation	Sodium to soil (accumulation within the technosphere)	Biomass production
Leaching of soluble compounds	Nutrient stock in soil	Irrigation; Pesticide application rate; Fertiliser application rate; Timing of fertiliser application	N to groundwater Pesticides to ground water	Ecotoxicity Eutrophication Human toxicity
Contamination	Natural background levels in soil	Fertiliser application rate; Type of fertiliser; Pesticide application rate; Type of pesticide; Yield of product	Grams of contaminant in soil (accumulation within the technosphere) Grams of contaminant in the product	Biomass production Ecotoxicity Human toxicity
Albedo	Reflectance	Tillage practice		Climate regulation

The impact pathway, proposed for midpoint assessment of soil functions (Figure 2), presents a more systematic construct that reflects the relationship between soil processes, soil quality measures and the subsequent impact of changes in these measures on soil function. It also incorporates the concept of intrinsic/inherent soil properties. However, it is still premised on land occupation/transformation as the only inventory flow to drive changes in soil function.

An alternate approach is to model soil processes in the inventory with the effect of interventions (inventory inputs, activities, and reference flows) on these processes directly expressed as elementary flows, and that the impact of these elementary flows on soil quality are what drive the impact assessment, rather than land use alone. Therefore, to facilitate a rational and clear link between elementary flows in LCI (that reflect the impact of interventions on soil processes) we suggest that in addition to information on land occupation/transformation, inventory include relevant elementary flows related to each of the soil processes. An example of this is how erosion is modelled as an inventory flow of soil loss (in grams) (Núñez *et al.* 2012).

Developing characterisation factors: The final step is to develop characterisation factors that link elementary flows to the mid-point impact indicators of soil quality and ability of the soil to produce biomass. This requires the additional work of identifying possible mechanisms for arriving at a common unit for soil function and its impact on biomass production. This is a significant area of work where a number of modelling approaches have been proposed. A recent review of these approaches (Vidal Legaz *et al.* 2016) concluded that none of the models provide a comprehensive solution; the more relevant a model was for assessing soil function the less applicable it was to LCA.

An alternate approach may be to use plant growth models such as APSIM (Keating *et al.* 2003) to determine how the change in soil attributes (SOC, pH, electrical conductivity, soil compression) affect biomass production. The characterisation factor then becomes a direct estimate of biomass in units of kg/ha, which can be easily characterised into impacts on available food, biofuel, carbon stores and vegetation cover, providing the link to climate regulation, ecosystem quality and human health.

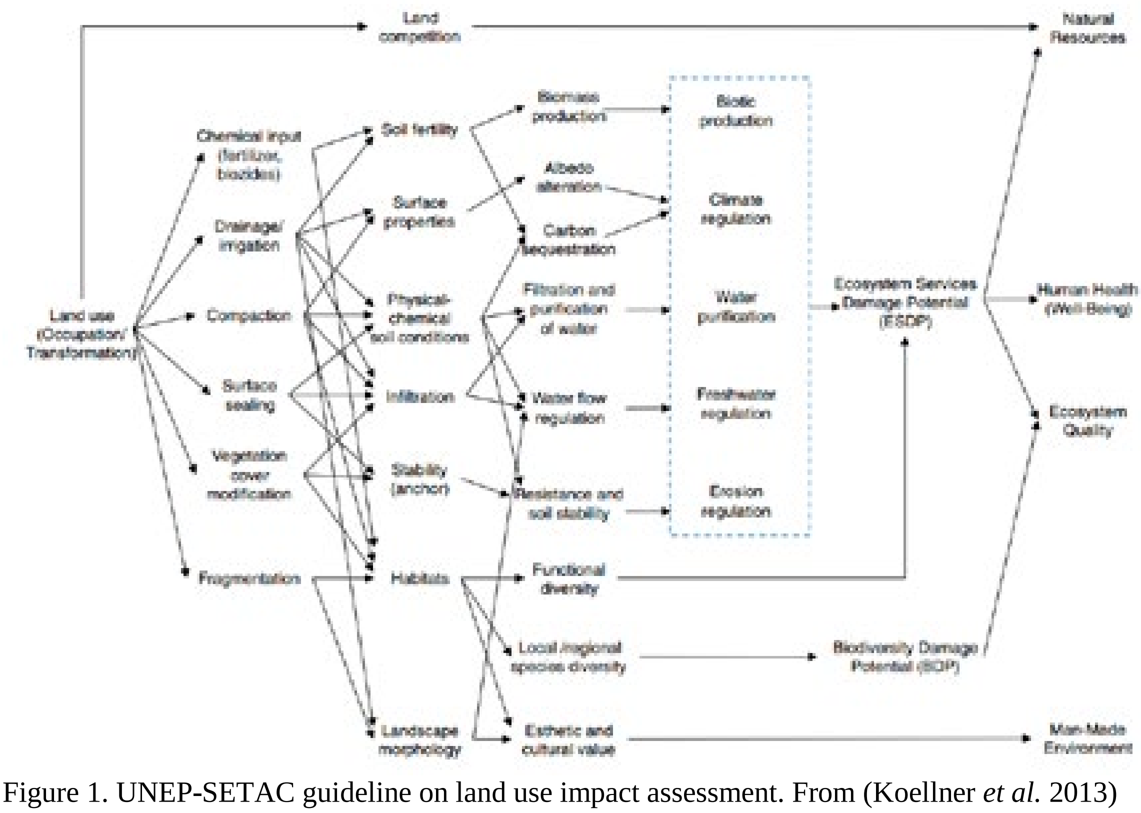

Figure 1. UNEP-SETAC guideline on land use impact assessment. From (Koellner *et al.* 2013)

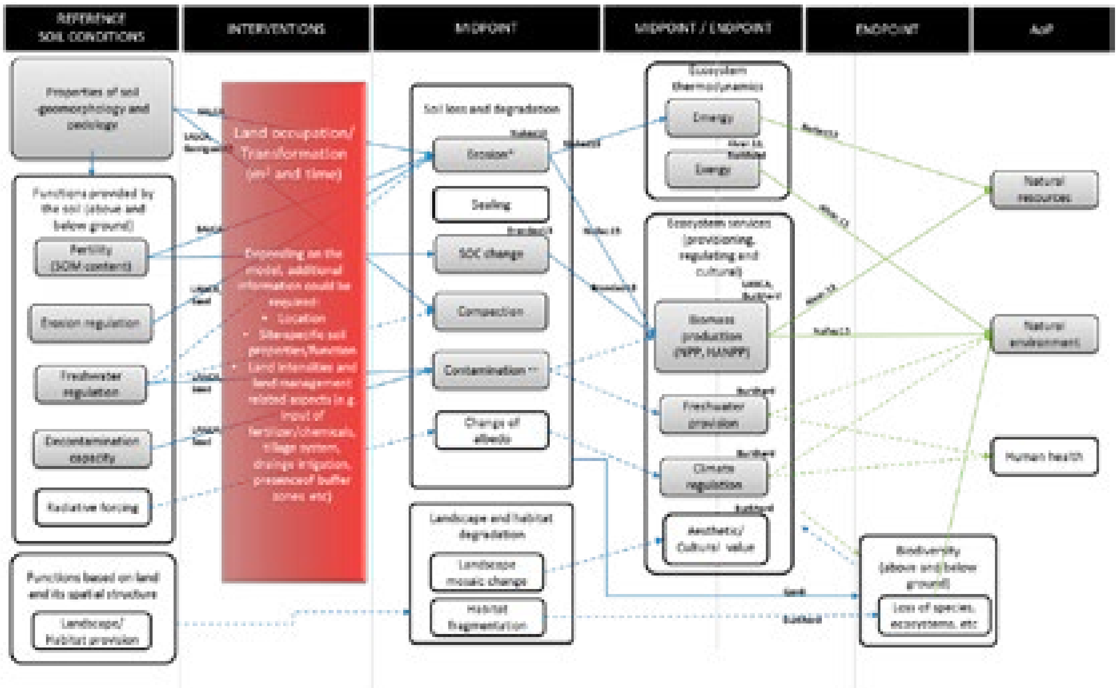

Figure 2. Land use impact pathway under discussion: Review of models, impact pathways, indicators and characterization factors towards a robust and comprehensive midpoint assessment of soil functions (Vidal Legaz *et al.* 2016).

Implementation of plant growth models is not easy due to the high level of parametrisation required. However, the increasing amount of data available from resources such as nation databases like the Soil and Landscape Grid of Australia (Terrestrial Ecosystem Research Network 2016), enables APSIM to be run spatially over many points, at the scale of an agro-ecological region. This approach is feasible and is currently being implemented to populate Australian agricultural LCI with elementary flows, such as change in SOC. APSIM could potentially be applied to LCIA, in manner similar to the way it is used to assess yield gaps (the gap between actual and potential crop yield) (yieldgapaustralia.com.au 2016). This concept is not that different from biotic production potential based on SOC (Brandão and i Canals 2013), but more representative of real production systems and encompassing the full range of soil quality attributes that contribute to biomass growth.

5. Conclusions

The development of LCA methods to incorporate soil function into LCA is at an exciting stage. We are now seeing scientists from across a range of domains exploring how to undertaken this complex task. This will bring knowledge, skills and tools from a wide perspective which will stimulate innovative solutions. The tools we now have available through the growth of GIS data (on land use, soils, and climate) open up the opportunity to parametrise LCI directly with the relevant elementary flows, and construct LCIA methods that are matched to real production systems. It is important that this international engagement continues, building on research and exploring new approaches, through Consensus Workshops and the formal UNEP-SETAC Sub-Task on Ecosystem Services.

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